# NAVAL POSTGRADUATE SCHOOL

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# THESIS

**A TWO-SIDED OPTIMIZATION OF BORDER PATROL INTERDICTION**

by

Halil Pulat

June 2005

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The United States Border Patrol (USBP) is responsible for interdicting unauthorized entry into the U.S. The USBP must decide how to allocate its detection and interdiction assets to maximize the probability of catching illegal aliens along the border. We study the case where an infiltrator can observe USBP preparations, and then choose a path into the U.S. We define the infiltrator's courses of actions to maximize the probability of escape, and then express the USPB's courses of actions to minimize that maximum achievable probability of escape. This case applies especially well to a signal entry, e.g. a well-planned, one-time smuggling of a weapon of mass destruction. We solve a sample problem for the U.S – Mexican border near Yuma, Arizona.

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# A TWO-SIDED OPTIMIZATION OF BORDER PATROL INTERDICTION

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The United States Border Patrol (USBP) is responsible for interdicting unauthorized entry into the U.S. The USBP must decide how to allocate its detection and interdiction assets to maximize the probability of catching illegal aliens along the border. We study the case where an infiltrator can observe USBP preparations, and then choose a path into the U.S. We define the infiltrator's courses of actions to maximize the probability of escape, and then express the USPB's courses of actions to minimize that maximum achievable probability of escape. This case applies especially well to a signal entry, e.g. a well-planned, one-time smuggling of a weapon of mass destruction. We solve a sample problem for the U.S – Mexican border near Yuma, Arizona.

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# LIST OF ACRONYMS

| | |
|---|---|
| AOR | Area of Responsibility |
| CBP | Customs and Border Protection |
| GAO | Government Accounting Office |
| ICAO | International Civil Aviation Organization |
| IMO | International Maritime Organization |
| INS | Immigration and Naturalization Service |
| USBP | United States Border Patrol |

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# EXECUTIVE SUMMARY

The Mexico-United States border is one of the world's largest drug smuggling corridors. Seventy percent of all cocaine, up to 80 percent of all marijuana and 30 percent of the heroin entering the United States comes from Mexico. Especially after the September 11 terrorist attacks, increased resources have been directed at deterring and preventing illegal aliens, drug smugglers, potential terrorists, and other criminals from entering the United States illegally. The case we study in this thesis especially addresses a signal entry, e.g. a one-time well-planned smuggling of a weapon of mass destruction.

There are official entry points along the border where migrants can enter legally. The USBP’s primary mission is to detect and prevent the entry of unauthorized aliens into the country, assist in the detection of possible terrorists, and interdict drug smugglers and other criminals between official points of entry.

Today, about 90 percent of the USBP agents are stationed at the southwest border. Between 1997 and 2004, 97 percent of the apprehensions due to illegal migration were made along the 1,952 mile-long southwest border. The USBP divides the southwest border into nine operational sectors, which encompass 80 percent of the illegal migrant traffic.

The main strategy employed by the USBP is “prevention through deterrence”. This strategy recommends that the Border Patrol try to prevent illegal alien entry rather than catch illegal aliens after they enter the country. However, the USBP employs checkpoints on highways, and air patrols over border areas for both interdiction and humanitarian purposes.

In 1994, the U.S. Attorney General proposed a five-part strategy to secure the border. This strategy calls for allocating additional Border Patrol resources first in the areas of highest known illegal activity. This strategy of strengthening the border at some relatively easy-to-infiltrate areas will push infiltration to other areas that are harder to exploit, and thus will make it harder for the infiltrators to traverse through the rough

features of the deserts, mountains and rugged terrain.  However, this approach is not necessarily optimal.  Although operationally intuitive approaches have great value, optimization can provide insights for planning purposes.

We discuss a worst-case scenario of infiltration through the border.  Optimally allocating border patrol assets to candidate locations, we evaluate the probability of detecting an infiltrator and also the probability of catching an infiltrator given that detection occurs.  We assume independence between probability of detection by different search assets, and detections on consecutive hops along the infiltrator's path.  We assume that the infiltrator can see the USBP's preparations and act accordingly to maximize his probability of escape.  Minimizing this maximum probability reveals a USBP action plan for the worst-case scenario where the infiltrator follows the minimum-risk path.

We solve a sample problem of border patrol interdiction problem for the U.S. – Mexican border near Yuma, Arizona.  Yuma sector is one of the nine sectors along the southwest border.  Yuma sector has stations in both Arizona, and California.  We examine only the area of responsibility of border patrol stations in Arizona portion of Yuma sector.  We develop a two-sided model to minimize the maximum achievable probability of escape by the infiltrator, and solve the problem as a mixed integer linear program.

# I. INTRODUCTION

This thesis develops an optimization model to allocate border patrol activities to interdict unauthorized entry, maximizing the probability of catching an infiltrator by using available assets subject to budget or availability constraints. We accomplish this through a network representation of a sample border area. This thesis develops a border patrol interdiction problem for the U.S.-Mexican border near Yuma, Arizona; the object is a generic model that could be applied to any border area.

## A. BACKGROUND INFORMATION

Illegal immigration and its consequences are a problem for many countries around the world, including the U.S. Unauthorized entry by aliens brings problems such as drugs, smuggling, increased crime rates and threat of infiltration by terrorists. For example, The Mexico-United States border is the world's largest drug smuggling corridor. 70 percent of all cocaine and up to 80 percent of all marijuana and 30 percent of the heroin entering the United States comes from Mexico [General Accounting Office (GAO) 1994]. Especially after the September 11 terrorist attacks, increased resources have been directed at deterring and preventing illegal aliens, drug smugglers, potential terrorists, and other criminals from entering the United States illegally [GAO 2004, p. 5]. The population of illegal immigrants living in the U.S. is between 9.2-10 million, based on current population surveys collected by the Census Bureau, according to the Center for Immigration Studies [Camarota 2004, p. 5].

> The 1,952 mile Southwest U.S. border has long been the flash point for illegal immigration into the United States: over the last seven years 97% of all illegal alien apprehensions have been made along the southwest border. The United States Border Patrol (USBP) divides the southwest border into nine operational sectors, two in California, two in Arizona, and five in Texas (Figure 1). Today, about 90% of USBP agents are deployed along the southwest border. Majority of them is concentrated in those nine corridors that encompass over 80% of the illegal migrant traffic [Nuñez-Neto 2004, p. 12].

There is a distinction made between “at entry points” and “between entry points.” USBP has no agents at the entry points.

> The USBP's primary mission is to detect and prevent the entry of unauthorized aliens into the country, assist in the detection of possible terrorists, and interdict drug smugglers and other criminals between official points of entry. USBP agents have no official role at points of entry; instead, Customs and Border Protection (CBP) inspectors stationed there are responsible for conducting immigrations, customs, and agricultural inspections on entering aliens. [GAO 2004, p. 5]

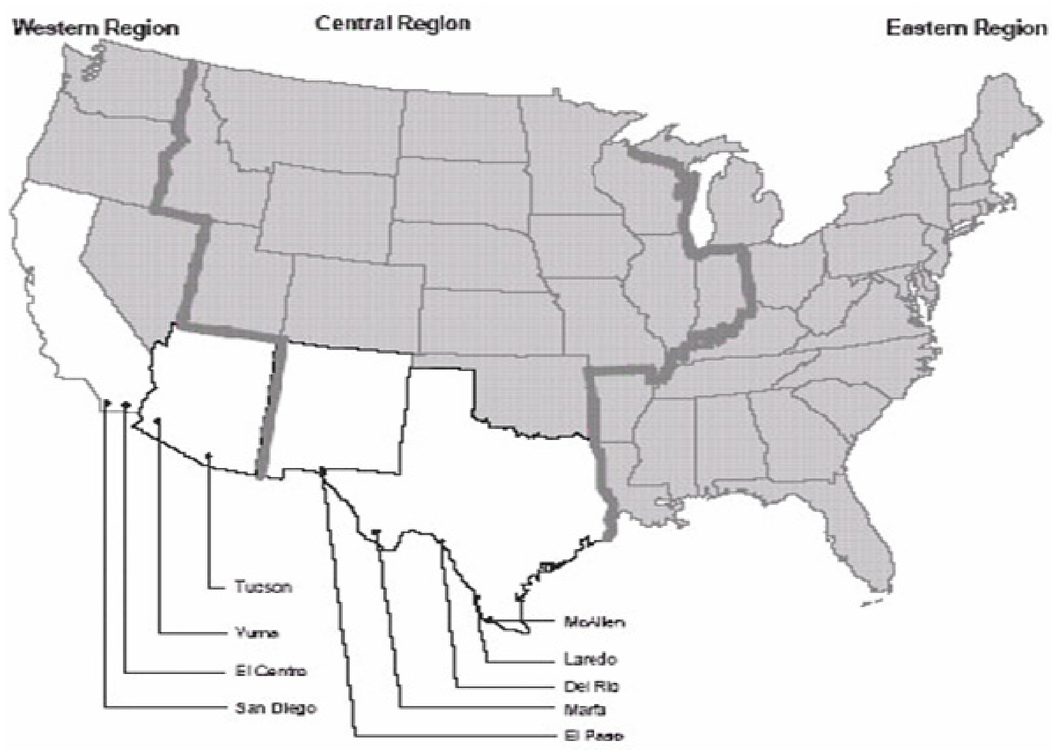


Figure 1. Nine Border Patrol Sectors [From: GAO 1997, p. 6].

## B. PROBLEM DESCRIPTION

Office of National Drug Control Policy recommends that the Border Patrol try to prevent illegal alien entry rather than catch illegal aliens after they enter the country [GAO 1994, p. 3].

In 1994, the U.S. Attorney General proposed a five-part strategy to strengthen the nation's borders. This strategy calls for the Border Patrol to:

> (1) allocate additional Border Patrol resources first with the areas of highest known illegal activity; (2) make maximum use of physical barriers; (3) increase the proportion of time Border Patrol agents spend on border enforcement activities; and (4) identify the appropriate mix of technology, equipment, and personnel needed for the Border Patrol. [GAO 1997, p. 1]

“The strategy to strengthen the border calls for prevention through deterrence; that is, to raise the risk of being apprehended for illegal aliens to a point where they will consider it futile to try to enter the United States illegally” [GAO 1997, p. 11].

This strategy can be regarded as greedy. Strengthening the border at some relatively easy-to-infiltrate areas (highly inhabited, relatively easier terrain) will shift infiltration to other areas that are harder to exploit, and thus will make it easier to detect those who traverse through the features of the deserts, mountains and rough terrain. It will be easier because those areas are much less populated. The strategy calling for allocating additional resources first to the areas of highest known illegal activity is not necessarily optimal, however.

A study by the University of Houston’s Center for Immigration Research shows that the overall number of illegal alien deaths on the U.S. – Mexico border has not increased, but there has been an increase in the number of deaths in the remote areas where illegal immigrants have traveled in an effort to avoid areas of greater enforcement along the border [GAO 1997, p. 51]. This border patrol plan is not necessarily inefficient, but we would like to optimize the border strength all along the border line, using available resources subject to some constraints suggested by the budget available.

Another consideration in border security and drug interdiction is that the infiltrators are adaptive: the infiltrator can see what the interdictor does, and thus can optimize infiltration with this prior knowledge, e.g. find clever ways to make it to the other side of the border minimizing the probability of being detected or apprehended. This is, in fact, what is seen by border patrollers. This is acknowledged by Alan D. Bersin, attorney general's special representative for the southwest border issues, U.S. Department of Justice:

> In 1994, when we began to review deployment and strategy, we started with this region, believing it was vital to deal first with our most difficult problems. We have had notable success. The immediate effect of Gatekeeper was to alter dramatically the entry pattern of undocumented aliens and force them into a much more inhospitable and rugged terrain. We then had to deploy agents to the new area of entry, while not neglecting to keep our reinforcements in Imperial County. One of the lessons we have learned from studying past strategies is that it is not sufficient to make progress in one area and then move on. The smugglers

> simply return to their old ways. What made the original route so popular e.g., ready access to highways and the opportunity quickly to reach big cities, will again be a draw. Therefore, we cannot simply move agents wholesale from California to Texas in order to deal with the problems in Texas. Instead, we have to reassess strategically and carefully manpower needs so that we do not backslide in one area as we work to handle another" [House of Representatives, Subcommittee on Immigration and Claims, Committee on the Judiciary (HOR) 1997, p. 121].
>
> Traffickers are shipping smaller amounts and varying their smuggling patterns and routes to minimize their losses. Not only have major drug organizations and independents changed some of their trafficking patterns; they have also modified their methods of communication, methods of concealment and the operation of their distribution networks to thwart law enforcement efforts [HOR 1997, p. 145].

Infiltrators learn from experience, and from open sources, where the Border Patrol uses its assets, and avoid being detected by changing their patterns accordingly.

There are several types of operations and activities that the USBP employs to interdict illegal entrants:

### 1. Operations and Activities in General

#### *a. Road Patrols*

Improved and semi-improved roads within a station's area of operations are patrolled regularly.

#### *b. Off-Road Operations*

Those operations are conducted by the USBP in addition to road patrols.

#### *c. Sensors*

These are small seismic or magnetic transmitters that are capable of detecting movement on the ground. When a sensor is activated, a signal, indicating the information when and where the sensor was activated, is sent to the nearest station. A patrol agent team is then sent to the area to search for the infiltrators.

#### *d. Air Operations (Heli-Patrol)*

Yuma sector's air operations are located at the U.S. Marine Corps Air Station. Air operations are primarily used in deterrence and search and rescue missions. Helicopters fly at altitudes visible to the infiltrators, and that is supposed to deter them. There are generalized flight routes within the sector. Deviations from those predetermined flight routes are only made to follow the tracks of persons or vehicles that are known to have made an illegal entry into the U.S. [Immigration and Naturalization Service (INS) 2002, p. 1-12].

#### *e. Fences and Barriers*

Fences are typically constructed in urban areas, and around official Ports-of-Entry. Fences are 10-15 feet-high. They are usually built within six feet of the border. USBP cannot protect the southern part of the fence, which makes it easier to be breached [INS 2002, p. 1-15]. We will exclude fencing as an option in USBP activities, because it is not a major component of the deterrence system, even though it is used largely along the border.

#### *f. Permanent and Portable Lighting*

These are permanent stadium type lights on 30-foot poles, or portable diesel powered lights. To be most effective, lighting should be used along with other assets [INS 2002, p. 1-17]. We will regard lighting as a contributor to probability of detection as it serves as part of the infrastructure, not as an operation or activity itself.

### 2. Operations and Activities in Yuma Sector

This sector (Figure 2) consists of Yuma, La Paz, and Mojave counties in Arizona; Riverside, San Bernardino, and Imperial counties in California; and Lincoln, Nye and White Pine counties in Nevada. However, we will just study the portions of the sector in Arizona (hereafter, we will address those portions in Arizona as the Yuma sector). There are two USBP stations in Yuma: Yuma and Wellton. The agents in Yuma station patrol 118 miles of the Mexican border. Table 1 shows activities within the Yuma station as of 2002 [INS 2002, p. 2-19].

#### *a. Yuma Station*

Existing infrastructure as of 2002 is shown in Table 1 and Figure 3 (All satellite images in this thesis are retrieved from the KEYHOLE software from www.keyhole.com).

#### *b. Wellton Station:*

This station has responsibility for 64 miles of the border. In addition to the activities and assets shown in Table 1, this station has an air-surveillance area. Daily 2.5-hour-long flights are made [INS 2002, p. 2-19] (Figures 4 and 5).

| | STATITION | |
|---|---|---|
| **ACTIVITY** | **YUMA** | **WELLTON** |
| Miles of Patrol Roads | 500 | 150 |
| Number of Ground Sensors | 214 | 47 |
| Number of Agents | 240 | 51 |
| Number of Remote Video Surveillance Sites | 16 | 0 |
| Miles of landing mat fence | 6.3 | 0 |
| Air patrols | YES | YES |
| Off Road Patrols | YES | YES |
| Checkpoint | 1PERMANENT<br>1TEMPORARY | 1 |

Table 1. Activities within Yuma and Wellton Stations [From: INS 2002, p. 2-19]

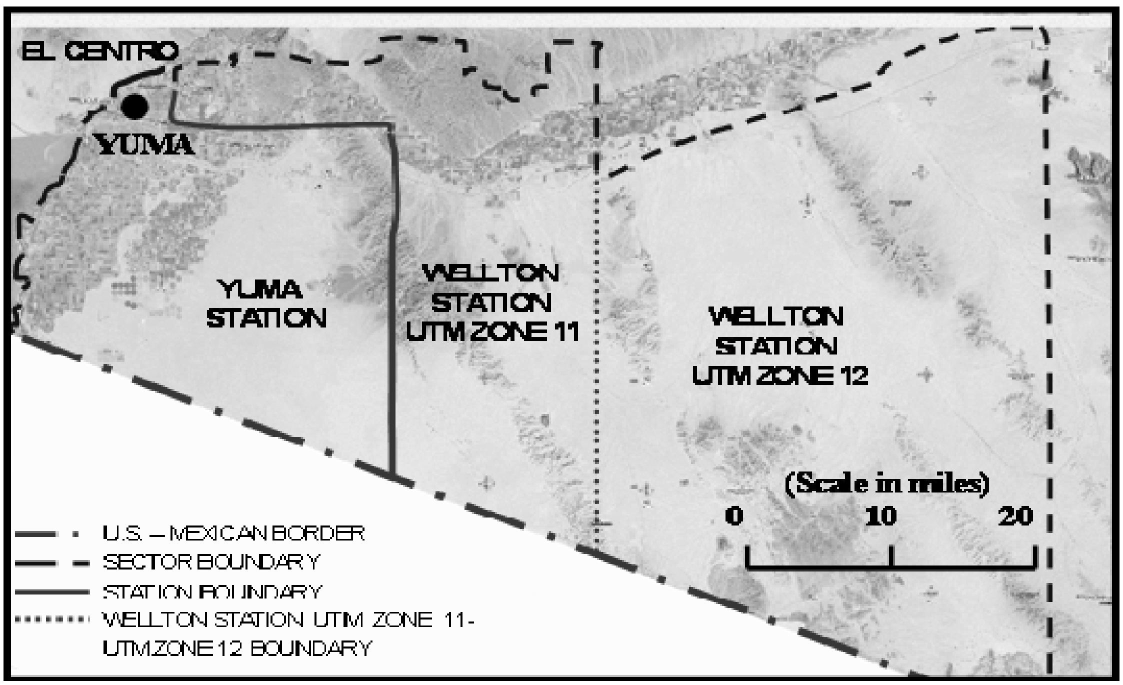


Figure 2. Yuma Sector (Arizona Stations) [After: INS 2002, p. 2-21]

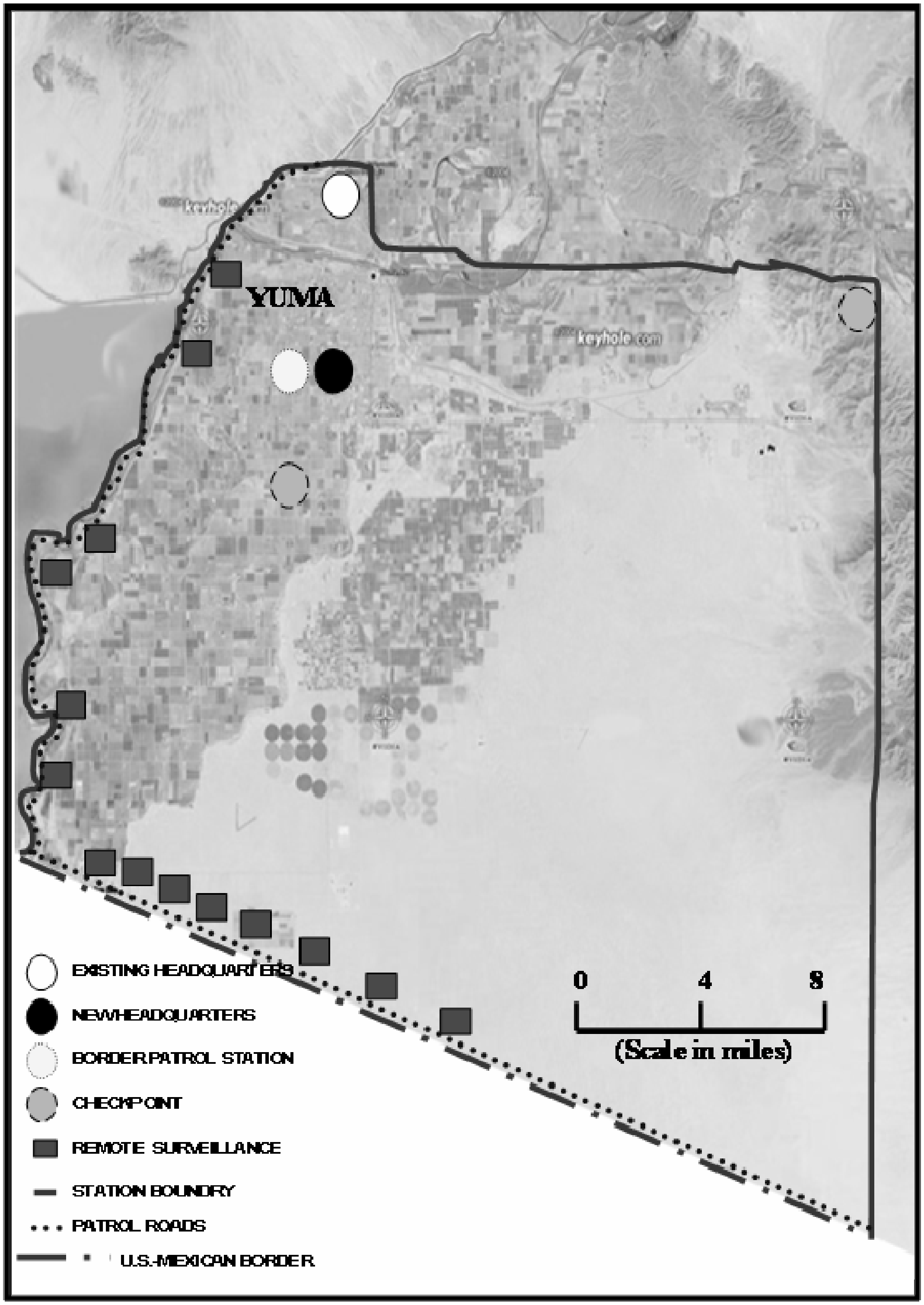


Figure 3. Yuma Station [After: INS 2002, p. 2-21]

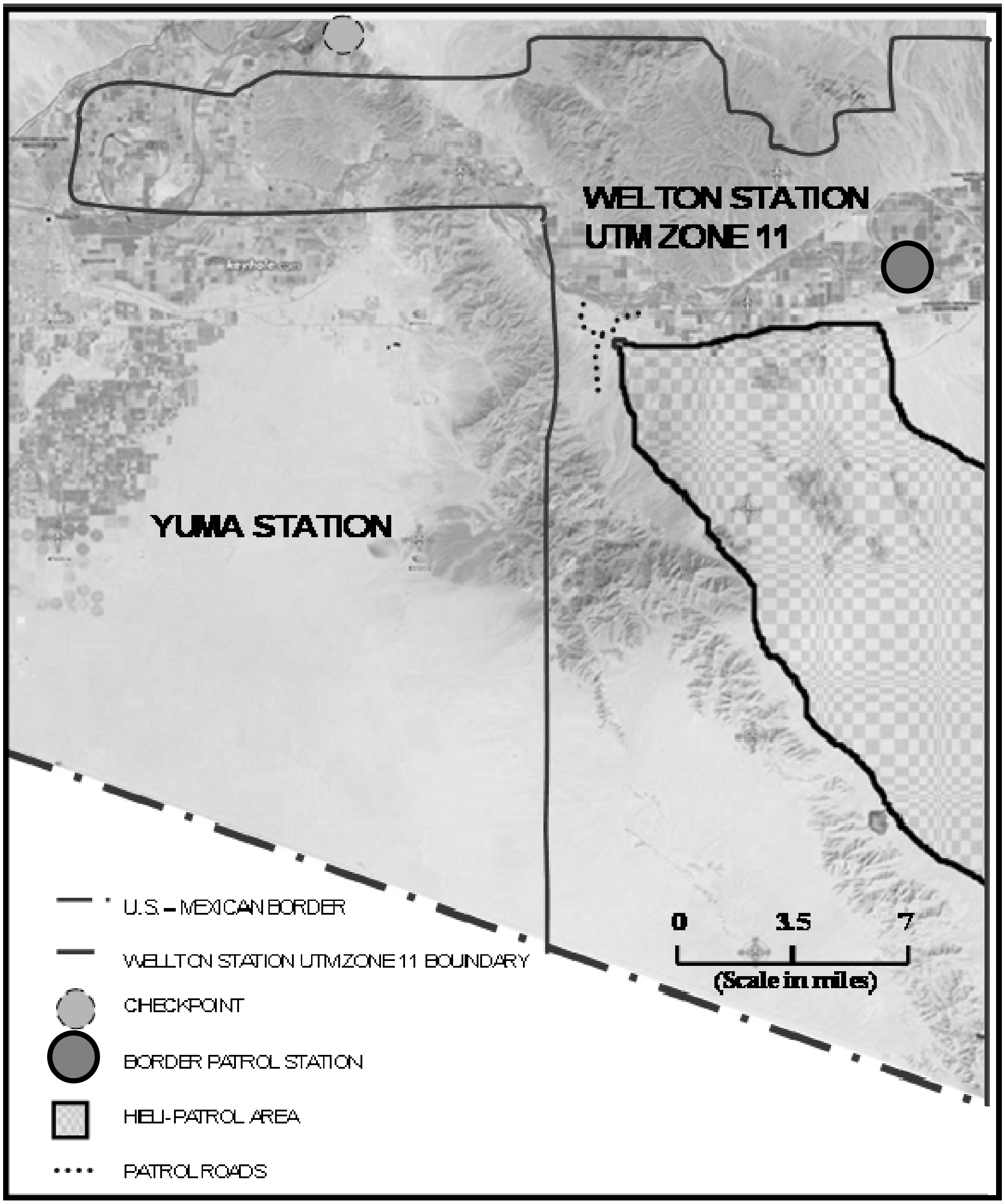


Figure 4. Wellton Station, UTM Zone 11 [After: INS 2002, p. 2-23]

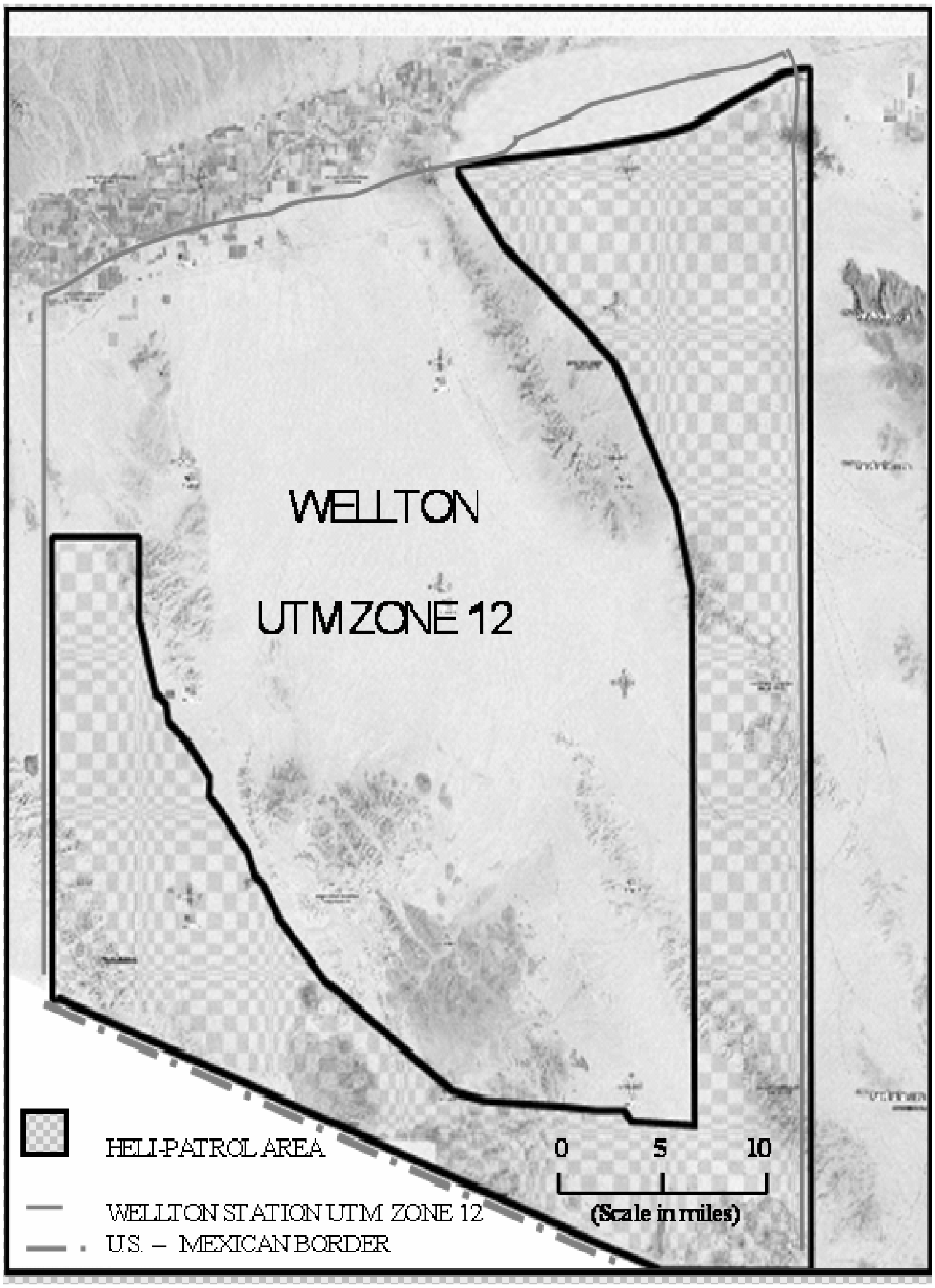


Figure 5. Wellton Station, UTM Zone 12 [After: INS 2002, p. 2-24]

## C. LITERATURE REVIEW

Wood [1993] introduces a deterministic network interdiction model that considers an adversary seeking to maximize flow through a capacitated network while an interdictor tries to minimize this maximum flow by interdicting arcs using available resources.

Cormican, Morton and Wood [1996] introduce a stochastic maximum-flow network interdiction model that has applications to interdicting drug smuggling and to reducing the effectiveness of an enemy's movement of troops, materiel, etc., in wartime. They also make extensions to include uncertain arc capacities and other realistic situations such as unsuccessful interdiction attempts.

Israeli and Wood [2002] study interdiction of an adversary's shortest path by using limited resources. Interdiction of an arc destroys an arc or increases its effective length (e.g., the cost of using this arc). In our problem, cost of using an arc is the natural logarithm of probability of capture that the infiltrator is subject to, if he decides to use that arc. An interdiction activity by USBP simply increases the probability of capture on some particular arcs.

Washburn and Wood [1995] describe a two-person zero-sum game for network interdiction. They consider a problem where a single evader seeks to move from a specified source to a specified destination while an interdictor tries to detect the evader by setting up an inspection point on one of the arcs. Each arc has a known probability of detection if the infiltrator decides to use that arc while the interdictor has his inspection point there. Their problem also has applications to interdicting drugs and illegal chemicals, and they solve cases with multiple interdictors, multiple evaders, and unknown sources and destinations. The evader seeks to minimize the detection probability, while the interdictor seeks to maximize this probability. The distinguishing feature of their study is that they provide a "path selection" strategy for the evader and an "arc-inspection" strategy for the interdictor. Their study best addresses a case in which the interdictor and the evader play this game over and over.

Morton, Pan, and Charlton [2003] develop a stochastic program for interdicting smuggled nuclear material. The optimization is stochastic because neither the source nor the destination for the smuggler is known at the time of allocating interdiction assets.

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# II. FORMULATION AND SCENARIO APPLICATION

We express our border security problem as a two-sided optimization model. The infiltrator aims to avoid getting caught while traveling from the southern side of the border (*s*) to north of the area of responsibility of USBP stations in the region (*t*). We don't allow the case where the infiltrator might consider traveling to the eastern or western side of the area of interest. There are two infiltration types. An infiltration may be on foot or in a vehicle. We solve these separately.

The interdictor (USBP), who can see the alternate paths that an infiltrator might choose, allocates limited defensive resources in anticipation of infiltration. The infiltrator, who can see the interdictor's preparations, seeks a minimum-risk path around or through the defenses to evade capture. Both opponents view the probability of capture as the objective, which the interdictor wants to maximize, and the infiltrator wants to minimize. The distinguishing feature of the models we introduce is the formal inclusion of *transparency* of USBP's assets. The best application of these models, for defender and/or infiltrator, is to prepare for a signal infiltration --- e.g., a one-time smuggling of a weapon of mass destruction. The defenses and infiltration suggested can be at once the best case and the worst case for either party. If either party follows the optimal plan, this is the best that can be done, and if either party follows some other plan, the opponent is better off.

## A. MODEL TERMINOLOGY

### 1. Network Representation

Each of the two stations in Yuma Sector's Arizona region has its own area of responsibility (AOR). These two areas of responsibility are combined for simplicity and treated as a single AOR.

The road network of the sample area is superimposed on a satellite image. We neglect parts of the network in the urban area for simplicity. The road segments that we neglect include those other than major connectors, highway portions, and major local roads. The road network for the non-urban areas is kept as is. Road intersections and land parcels between road segments are nodes (*n*) of the network (*alias i, j*).

Each road segment is treated as an arc that USBP can observe to increase the overall probability of capture ($P_c$).

Each road segment connecting two nodes $i$ and $j$ is represented as arc $(i, j)$. We define $P_d$ on a given arc as the *probability of detection* when that particular arc is traversed by the infiltrator. Each arc may be a highway, major connecter, local road, or a trail, and this influences the probability of detection ($P_d$) on that arc.

Each arc has a length (in miles), and a transition time (in hours) associated with it. Transition time on each arc is determined by the arc type and the intrusion type.

The terrain is divided into homogeneous parcels, and each parcel is treated as a node, so we can allow traveling off the roads, and between a road segment and a land parcel (Figures 6 and 7).

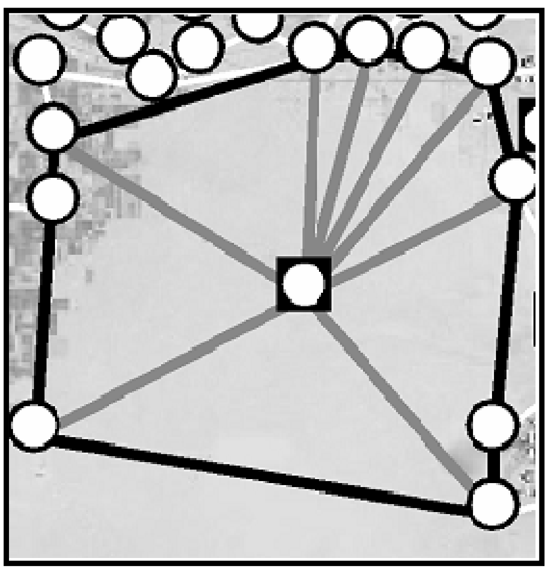

Figure 6. A Sample Land Parcel

The black arcs mark the boundaries of the sample land parcel. White ovals indicate road intersections. The black squares with white ovals in them represent centers of land parcels. The gray arcs are artificial arcs from the center of the land parcel to road intersections.

### 2. Infiltrator's Courses of Action

The infiltrator decides which arcs to traverse. We allow human infiltrators to traverse on the terrain and road segments, while we restrict vehicle infiltrators to road segments only.

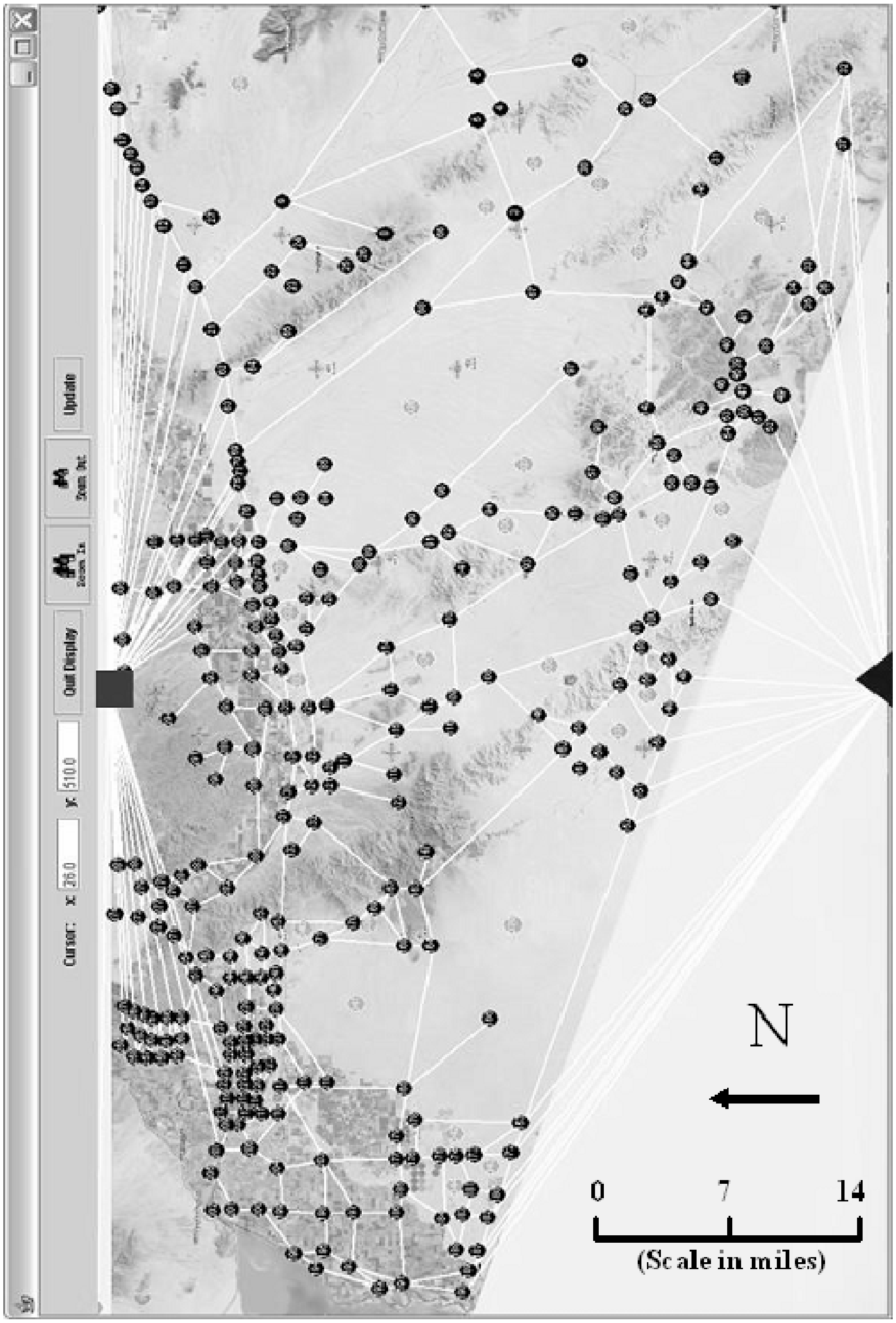


Figure 7. Road Network in Yuma, Arizona

Black ovals indicate road intersections, and the gray ovals indicate centers of land parcels. The triangle represents the source, *s*. The rectangle represents the destination, *t*. We assume that the infiltrator is no longer subject to capture once he reaches *t*. The arcs that emanate from *s* represent the possible entry ways, and the arcs that connect to *t* represent possible exit ways. The land parcels are not connected to road intersections in the figure for clarity.

### 3. USBP's Courses of Actions

USBP employs available *defensive actions* ($a$) to interdict the infiltrator's unauthorized entry to U.S. soil. A defensive action might either be a "*detection*" action ($d$) or a "*capture*" action ($c$). A detection action can only lead to detection, whereas a capture action can lead to detection and capture of an infiltrator (Figure 8).

A detection action or a capture action simply increases the probability of detection on a given set of arcs. We assume that the expected cost resulting from employing a defensive action ($P_d$) is known by both the infiltrator and the interdictor.

There are *detection methods* that a defensive action can employ (*heli-patrol*, *road patrol*, *off-road operation*, *check point*, *remote observation post*, and *sensors*). Each defensive action employs a specific detection method (Figure 9). The $P_d$ on a given arc is determined by the physical features of that arc, and the detection method that is employed by that particular defensive action.

Remote observation posts, check points and road patrols are employed by capture actions. Sensors and heli-patrol detection methods are employed by detection actions.

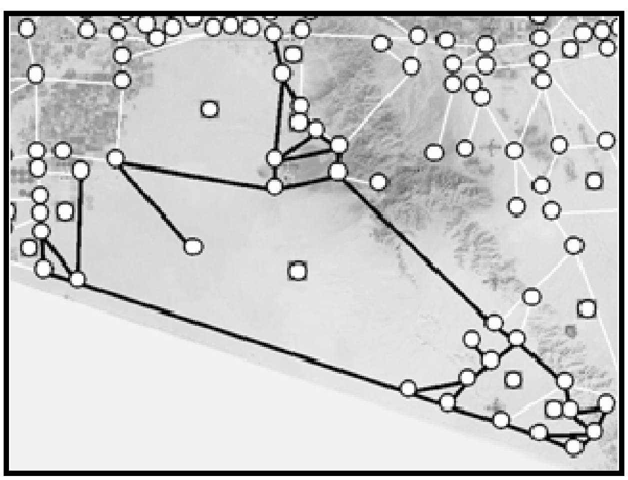

Figure 8. Illustration of a Defensive Action

A defensive action is associated with two elements: a set of arcs that can be influenced by this action, and a detection method that it employs. As an example, a defensive action could be observing a particular portion of the AOR (e.g., a set of arcs) from air (e.g., a detection method). Black lines indicate arcs that are influenced by such a defensive action. Probability of detection on one of these arcs is determined by the physical features of the arc and the detection method that is used.

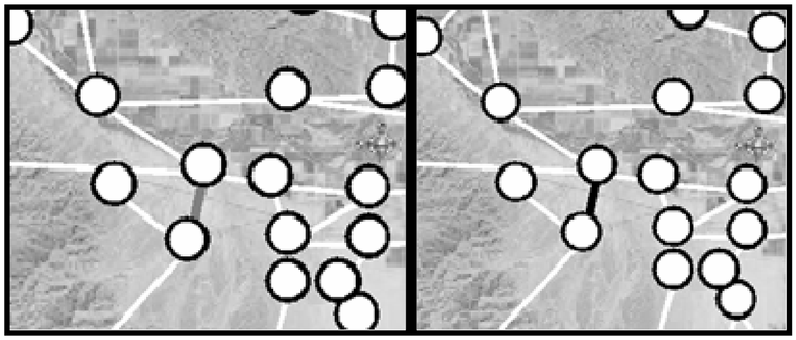

Figure 9. Two Separate Defensive Actions on the Same Arc, with Different Detection Methods

In this example, there are two different defensive actions that can influence the $P_d$ on the same arc (each of them is displayed on a separate picture of the same area). The picture on the left illustrates an arc defended by a defensive action that employs a check point (the gray arc). The picture on the right illustrates the situation where the same arc is defended by a separate defensive action that employs a road patrol (the black arc). The probability of detection on that arc is determined assuming independence between these separate defensive actions. The detection method that a defensive action can employ is pre-determined, as well as the arcs that can be influenced by that defensive action.

We divide the AOR into grids, each of which represents a *locality* where a set of defensive actions may be employed (Figure 10).

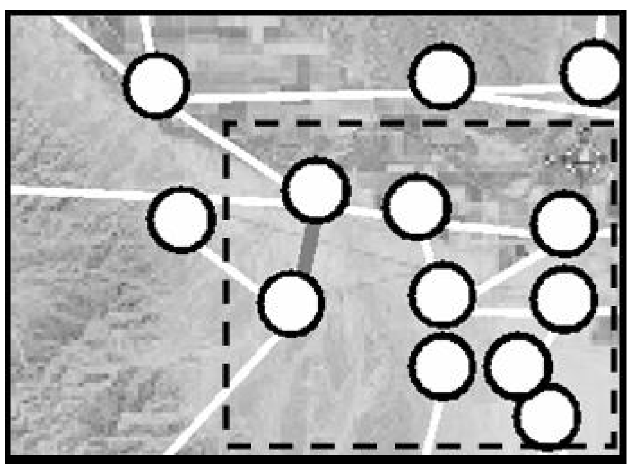

Figure 10. Illustration of a Locality

The gray arc illustrates a capture action that employs a check point as a detection method. The dashed-line rectangle indicates the locality of that particular catch option. A locality might have more than one capture action. We define that locality as the locality of capture action *c*.

The USBP decides which capture actions to employ ($X_c$) and which detection actions to employ with the support of a capture action from one of the neighboring localities ($R_{dl}$).

When detection is made by a detection action, a capture action from the closest locality is informed of the detection. A random search then starts to find the infiltrator around the neighborhood of the detection (i.e., *any* capture action from the closest locality carries out the search). The probability of capture given detection occurs is a function of the distance between the locality of the catch action that carries out the search, and the arc where the detection occurs (Figure 11).

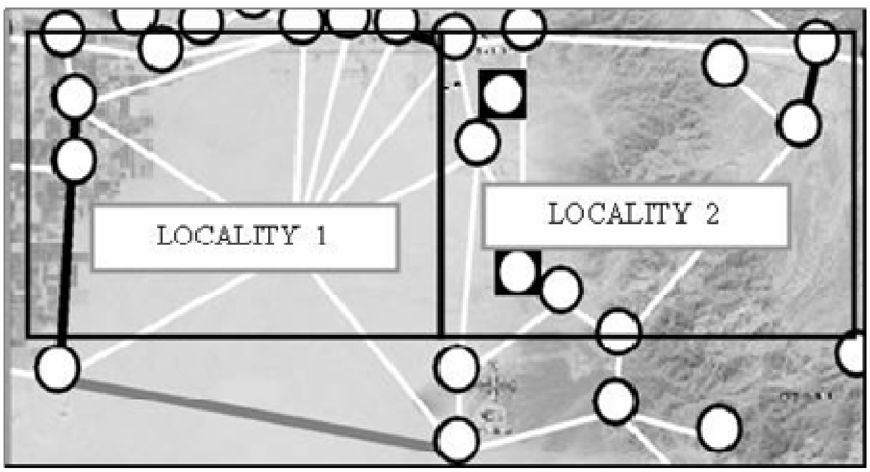


Figure 11. Support of a Detection Action with a Capture Action from a Locality. This example illustrates the idea of supporting a detection action with a capture action from a locality. The black arcs indicate catch actions, and the gray arc indicates a detection action. Two black rectangles mark two localities. If detection occurs on the gray arc, the detection action that makes the detection has no capability to catch the infiltrator (detection actions can only lead to detection). There are two catch actions employed in locality 1, and one catch action employed in locality 2. Once the detection occurs on the gray arc, any catch action from the closest locality to that arc (here, locality 1) is informed of that detection and a random search starts around where the detection occurs. In reality, an intelligent search would be carried out in the presence of such detection; hence, these random search probabilities of capture provide a worst case scenario. If detection is made by one of the capture options in, for instance, locality 1, then the action itself can lead to detection and capture. Hence, it is not supported with any other capture action from other localities.

This model set-up favors a capture action versus a detection action (i.e., if a detection action is not supported by a capture option, it is useless).

Let $PC_{ijl}$ be Pr {capture of an infiltrator traversing *arc* ($i$,$j$) by any capture action from locality $l$ given detection occurs on *arc* ($i$,$j$)}. We use random search theory of an expanding area to evaluate $PC_{ijl}$ [Wagner, Mylander, Sanders 1999].

$$PC_{ijl} = 1 - \exp\left(-\frac{wv}{\pi u^2 t_0}\frac{t}{(t_0 + t)}\right) \qquad \text{(p1)}.$$

In (p1), $w$ is the sweep-width of the searcher, $v$ is the speed of the searcher, and $u$ is the speed of the infiltrator. While $t$ is search time, $t_0$ denotes the response time, which is the time interval between when the capture action is informed of the detection and when he arrives where the detection occurs. We find shortest transition times from each locality to every single arc in the network (optimum response times ($t$) between each arc and each locality). Let $PC_{ijal}$ be the probability of capture by any capture action from locality $l$, if the infiltrators is detected by defensive action $a$ while traversing *arc* ($i$,$j$).

$PC_{ijal} = PC_{ijl}$ X Pr {detection is made by defensive action $a$ on *arc* ($i$,$j$)}

As an example, if the probability of detection on "arc (n1,n2)" by defensive action "a1" is 0.2, and the probability of capture by a capture action from locality "l1" given that detection occurs on "arc (n1,n2)" is 0.3, then "PC (n1,n2,a1,l1)"=0.2*0.3=0.06.

## B. DETERMINING PROBABILITY OF DETECTION BY DIFFERENT DETECTION METHODS

$P_d$ depends upon which detection method makes the detection, and where the detection is made. Details of effects of arc type, arc length, transition time, and other factors on $P_d$ differ by detection method.

### 1. $P_d$ by Road Patrol

We define a road patrol as an 8-hour patrol by a vehicle on the ground. Given a detection opportunity, we assume that the probability of detecting an infiltrator on a given road segment is equal to the proportion of the patrol time over that road segment to the total patrol time (8 hours). If the road patrol vehicle and the infiltrator are on the same road segment at any time, a detection opportunity is assumed to occur.

### 2. $P_d$ by Heli-Patrol

We identify separate candidate regions in the AOR in which USBP can employ heli-patrol. We limit heli-patrol method to deserts, plains, and valleys. *Pd* by heli-patrol is a function of the area that the search is carried out ($A$), speed of the aircraft ($v$), amount of time the searched object remains in the search area together with the searcher ($t$), and sweep width of the aircraft ($w$). Search time $t$ is determined by the transition times on those particular arcs that the infiltrator decides to traverse. We assume a helicopter speed of 120 knots, an altitude of 500 feet, a visibility condition of 10 nautical miles, and an environment with a 15-60 percent level vegetation or hilly terrain. We extract sweep width values using Tables 2 and 3.

An aircraft under the assumptions we make has $w$=0.5 nautical miles when the searched object is a person, and 1.3 nm for a vehicle. We multiply those values with correction factors of 0.5 and 0.7 according to the assumptions we make, and we get the corrected (actual) w values of 0.25 and 0.91, respectively. Let c denote the constant value wv/A. Pd for a random search in a given search area ($A_s$), is given by equation (p2) [Wagner, Mylander, Sanders, 1999, p. 174].

$$P_d = 1 - e^{(-ct)} \quad . \qquad \text{(p2)}$$

| Search Object | Visibility (km(NM)) | | | | | |
|---|---|---|---|---|---|---|
| | Height(m(ft)) | 6(3) | 9(5) | 19(10) | 28(15) | 37(20) |
| Person | 150(500) | 0.7(0.4) | 0.7(0.4) | 0.9(0.5) | 0.9(0.5) | 0.9(0.5) |
| | 300(1000) | 0.7(0.4) | 0.7(0.4) | 0.9(0.5) | 0.9(0.5) | 0.9(0.5) |
| | 450(1500) | - | - | - | - | - |
| | 600(2000) | - | - | - | - | - |
| Vehicle | 150(500) | 1.7(0.9) | 2.4(1.3) | 2.4(1.3) | 2.4(1.3) | 2.4(1.3) |
| | 300(1000) | 1.9(1.0) | 2.6(1.4) | 2.6(1.4) | 2.8(1.5) | 2.8(1.5) |
| | 450(1500) | 1.9(1.0) | 2.6(1.4) | 3.1(1.7) | 3.1(1.7) | 3.1(1.7) |
| | 600(2000) | 1.9(1.0) | 2.8(1.5) | 3.7(2.0) | 3.7(2.0) | 3.7(2.0) |
| Aircraft less than 5700 kg. | 150(500) | 1.9(1.0) | 2.6(1.4) | 2.6(1.4) | 2.6(1.4) | 2.6(1.4) |
| | 300(1000) | 1.9(1.0) | 2.8(1.5) | 2.8(1.5) | 3.0(1.6) | 3.0(1.6) |
| | 450(1500) | 1.9(1.0) | 2.8(1.5) | 3.3(1.8) | 3.3(1.8) | 3.3(1.8) |
| | 600(2000) | 1.9(1.0) | 3.0(1.6) | 3.7(2.0) | 3.7(2.0) | 3.7(2.0) |

Table 2. Sweep Widths for Visual Land Search

For example, 0.7(0.4) is the sweep width for an aircraft at an altitude of 150 meters (i.e., 500 feet), when the visibility is 6 kilometers (3 nautical miles) [International Maritime Organization (IMO), International Civil Aviation Organization (ICAO), 1999].

| **Search Object** | **15-60% Vegetation or Hilly** | **60-85% Vegetation or Mountainous** | **Over 85% Vegetation** |
|---|---|---|---|
| **Person** | 0.5 | 0.3 | 0.1 |
| **Vehicle** | 0.7 | 0.4 | 1.1 |
| **Aircraft less than 5700 kg** | 0.7 | 0.4 | 2.1 |
| **Aircraft over 5700 kg** | 0.8 | 0.4 | 3.1 |

Table 3. Correction Factors- Vegetation and High Terrain

For example, sweep width value needs to be multiplied by 0.5 if a searched object is a person and the terrain has 15-60 percent vegetation or it is hilly [IMO, ICAO, 1999].

This formula assumes a continuous search time (*t*) in a given search area. However, we define $P_d$ values being associated with arcs. Let $Pnd_n$ denote the individual non-detection probability at the time that the infiltrator traverses *n*th arc in $A_s$, and $Pd_n$ denote the detection probability. We assume that a total number of *n* arcs will be traversed during the search. Let $P_{nd}^n$ denote the total probability of no detection at the end of the *n*th search, and $P_{nd}^t$ denote the non-detection probability in [0, t]. From (p2), we get:

$$P_{nd}^t = e^{-ct} \quad . \qquad \text{(p3)}$$

Assuming independence:

$$P_{nd}^n = \prod_1^n (1 - Pd_n) \quad . \qquad \text{(p4)}$$

Let $t_n$ be the transition time on the *n*th arc.

$$t = t_1 + t_2 + t_3 \ ... \ t_n \qquad \text{(p5)}$$

$$Pd_n = 1 - e^{-ct_n} \qquad \text{(p6)}$$

$$P_{nd}^n = \prod_1^n (1 - Pd_n) = \prod_1^n (e^{-ct_n}) = e^{-ct} = P_{nd}^t \quad . \qquad \text{(p7)}$$

Thus, non-detection probability for a given candidate heli-patrol area in [0, t] can be partitioned into a series of independent non-detection probabilities on each arc based on the transition time on that individual arc.

#### 3. $P_d$ by off-Road Operations

Pd for off-road operations is determined by the use of random search theory, this time *v* being 10 miles per hour and *w*=400 feet.

#### 4. $P_d$ by Check Points

We assume that *Pd* by a check point is 0.15.

#### 5. $P_d$ by Remote Observation Posts

A remote observation post operates like a check point. We assume that *Pd* by a remote observation post is 0.4, to reflect the higher proportions of people or vehicles that can be stopped at those points due to lighter traffic.

#### 6. $P_d$ by Sensors

We assume that *Pd* by a sensor is 0.4 for a vehicle and 0.2 for a human.

## C. MATHEMATICAL DEVELOPMENT OF THE TWO-SIDED DETECTION AND CAPTURE OPTIMIZATION PROBLEM

The following optimization models express the opposing goals of an interdictor, and an infiltrator.

#### 1. Indices and Index Sets

| | |
|---|---|
| $n \in N$ | node, representing a road intersection or an area parcel in the Area of Responsibility (AOR), (alias *i*,*j*) |
| $s \in N$ | source node, origin of any infiltration path |
| $t \in N$ | destination node of any infiltration path |
| $(i, j) \in A$ | a directed arc (adjacency) from node *i* to node *j* in D-graph *A*. |
| $a \in Q$ | defensive action |
| $c(a) \in C \subseteq Q$ | a defensive "capture" action that can lead to detection and capture of an infiltrator |
| $d(a) \in D \subseteq Q$ | a defensive "detection" action that can lead to detection of an infiltrator, and that can only lead to capture in conjunction with a supporting capture action ( $C \vee D = Q,\ C \wedge D = \varnothing$ ) |
| $l \in L$ | locality, or area where a defensive action can be employed |
| $l_c$ | locality of capture action c |

$g \in G$ — type of resource restriction on defensive actions (e.g., helicopters, patrol vehicles, personnel, etc.)

### 2. Data

$r_{ij}$ — intrinsic risk of detection and capture if an infiltrator traverses arc (i,j), regardless of any USBP action.

$PC_{ijal}$ — if an infiltrator traverses arc (i,j) and the detection is made by defensive action a, the probability that a catch action from locality l will lead to capture. A capture action c(a) is based in $l_c$, while a detection action d(a) is supported with a capture action from one of a number of localities.

$lnPNC_{ijal} \equiv \ln(1 - PC_{ijal})$.

$cost_a$ — cost of employing defensive action *a*

*max_cost* — maximum budget for the cost of all defensive actions

$resource_{a,g}$ — defensive action a consumption of resource type g

$availability_g$ — maximum resource type g available for all defensive actions

### 3. Decision Variables

$R_{dl} \in \{0,1\}$ — binary decision to employ detection action d with support of a capture option from locality l

$X_c \in \{0,1\}$ — binary decision to employ capture option c in locality $l_c$

$Y_{ij} \in \{0,1\}$ — binary decision by the infiltrator to traverse arc (i,j) on a path from source node s to destination node t

### 4. Minimax Optimization of Probability of Non-Catch [Dual Variables]

$$\min_{X,R}\left\{\begin{array}{lll}
\max\limits_{Y} \prod\limits_{(i,j)\in A}\left((1-r_{ij})\prod\limits_{d,l}(1-PC_{ijdl}R_{dl})\prod\limits_{c}\left(1-PC_{ijcl_c}X_c\right)\right)^{Y_{ij}} & \text{(i0)} & \\
\sum\limits_{(n,j)\in A} Y_{nj} - \sum\limits_{(i,n)\in A} Y_{in} = \begin{cases} +1 \text{ for source, } n = s \\ 0 \quad \forall n - \{s,t\} \\ -1 \text{ for destination, } n = t \end{cases} & \begin{array}{l}\text{(i1)}\\ \text{(i2)}\\ \text{(i3)}\end{array} & \begin{array}{l}[\mathrm{W_s}]\\ [\mathrm{W_n}]\\ [\mathrm{W_t}]\end{array} \\
Y_{ij} \geq 0 \qquad\qquad \forall (i,j) \in A & \text{(i4)} &
\end{array}\right\}$$

The objective function (i0) expresses the probability that the infiltrator will evade capture while traversing his chosen path from node *s* to node *t*. Each arc (*i*,*j*) is vulnerable to detection and capture by parties other than USBP, and to a number of USBP detection actions *R* and capture actions *X*. Each capture probability *PC* conveys whether or not its detection or capture action can influence the outcome: for any arc (*i*,*j*), detection action *dl* or capture action *c* will offer a capture probability *PC* sufficiently large to signal a reasonable alternative, or not. Constraints (i1-i3) enforce conservation of flow along an infiltrator path: the infiltrator must depart from node *s* (i1), must depart any intermediate node he enters (i2), and must arrive at node *t* (i3). The non-negativity restrictions (i4) actually suffice, for any fixed *R* and *X*, to render binary values for *Y*.

The above minimax formulation makes the implicit assumption that the infiltrator moves last; that is, the infiltrator chooses the path in the knowledge of all countermeasures already employed by USBP. We define that as the transparency of USBP's assets. This "transparency" assumption is pessimistic from the view point of USBP.

Objective function (i0) is non-linear in *Y*, *X* and *R*. However, exploiting the fact that maximizing the logarithm of a function maximizes the function, we can reformulate as follows:

(i0) is equivalent to:

$$\max_{Y} \ \ln\left( (1-r_{ij}) \prod_{(i,j)\in A} \left( \prod_{d,l} (1-PC_{ijdl}R_{dl}) \prod_{c} (1-PC_{ijcl_c}X_c) \right) Y_{ij} \right) \qquad \text{(i5)}$$

$$= \max_{Y} \sum_{arc(i,j)\in A} \left( \ln(1-r_{ij}) + \sum_{d,l} \ln\left(1-PC_{ijdl}R_{dl}\right) + \sum_{c} \ln\left(1-PC_{ijcl_c}X_c\right) \right) Y_{ij}. \qquad \text{(i6)}$$

Because *X*, *R* and *Y* are binary, (i6) is equivalent to:

$$\max_{Y} \sum_{arc(i,j)\in A} \left( \ln(1-r_{ij}) + \sum_{d,l} \ln\left(1-PC_{ijdl}\right) R_{dl} + \sum_{c} \ln\left(1-PC_{ijcl_c}\right) X_c \right) Y_{ij} \ . \qquad \text{(i7)}$$

Substituting $lnPNC_{ijal}$ for $\ln(1-PC_{ijal})$, the revised objective function becomes:

$$\max_{Y} \sum_{arc(i,j)\in A} \left( \ln(1-r_{ij}) + \sum_{d,l} lnPNC_{ijdl} R_{dl} + \sum_{c} lnPNC_{ijcl_c} X_c \right) Y_{ij} \ . \qquad \text{(i8)}$$

### 5. Limits on USBP's Actions

$$\sum_{d,l} cost_d R_{dl} + \sum_c cost_c X_c \leq max\_cost \qquad \text{(u1)}$$

$$\sum_c resource_{cg} X_c + \sum_{d,l} resource_{dg} R_{dl} \leq availability_g \qquad \forall g \in G \qquad \text{(u2)}$$

$$R_{dl} \leq \sum_{c|l=l_c} X_c \qquad \forall d \in D, l \in L \quad \text{(u3)}$$

$$\sum_l R_{dl} \leq 1 \qquad \forall d \in D \qquad \text{(u4)}$$

$$X_c \in \{0,1\} \qquad \forall c \in C \qquad \text{(u5)}$$

$$R_{dl} \in \{0,1\} \qquad \forall d \in D, l \in L \quad \text{(u6)}$$

Constraint (u1) limits the cost of employing detection and capture actions. Each constraint (u2) limits a resource consumed by detection and capture actions. Each constraint (u3) assures that a detection action *d* is supported by some capture action from locality $l_c$. Each constraint (u4) limits each detection action to be supported with a capture action from at most one locality. Note that a capture action can be committed to any number of defensive actions *d*. (u5) and (u6) require binary decisions.

### 6. Two Sided Mixed Integer Optimization Model to Minimize Maximum Achievable Probability of Escape

For a fixed set of defense decisions, $X^*$ and $R^*$; the infiltrator's problem is a linear program that will render an intrinsically integer optimum infiltration solution $Y^*$. We substitute the dual of infiltrator's maximization problem yielding a mixed integer linear program.

$$\min_{W,R,X} W_s \text{-} W_t \quad \text{(t0)}$$

s.t. $$W_i - W_j \geq \ln(1-r_j) + \sum_{d,l} lnPNC_{ijdl} R_{dl} + \sum_c lnPNC_{ijcl_c} X_c$$

$$\forall\ arc(i,j) \in A \quad \text{(t1)}$$

$$\sum_{d,l} cost_d R_{dl} + \sum_c cost_c X_c \leq max\_cost \quad \text{(t2)}$$

$$\sum_c resource_{cg} X_c + \sum_{d,l} resource_{dg} R_{dl} \leq availability_g$$

$$\forall g \in G \quad \text{(t3)}$$

$$R_{dl} \leq \sum_{c \mid l = l_c} X_c \qquad \forall d \in D, l \in L \quad \text{(t4)}$$

$$\sum_l R_{dl} \leq 1 \qquad \forall d \in D \quad \text{(t5)}$$

$$X_c \in \{0,1\} \qquad \forall d \in D \quad \text{(t6)}$$

$$R_{dl} \in \{0,1\} \qquad \forall d \in D, l \in L \quad \text{(t6)}$$

$$W_s = 0 \quad \text{(t7)}$$

$$W_{i,j} \ \text{URS} \qquad \forall arc(i,j) \in A \quad \text{(t8)}$$

We can then recover an infiltrator's optimal infiltration plan by solving the above problem, and then substituting X*, and R* into the original maximization problem to obtain Y.

**D. A SAMPLE YUMA, ARIZONA SCENARIO**

We identify five candidate heli-patrol, and three road patrol areas. We limit check-points to highways and urban areas, and remote observation posts to remote areas close to the border. We do not allow heli-patrol and road patrol on highways and urban areas. The only arcs with sensors are the ones at the entry points along the border. There are 522 candidate defensive actions, 344 nodes representing road intersections and land parcels (26 land parcels), 1200 arcs, and six defensive options available. We use availability constraints only (e.g., availability of "helicopters" is no more than two), and use a commercial map to identify road types, length, and geographical features. We then determine the *probability of detection* on each arc given a *defensive action* and multiply that value by the *probability of capture* value that we obtain by using shortest path distances from each arc to each locality. We identify 57 such localities, and solve the problem for various cases.

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# III. RESULTS AND ANALYSIS

We evaluate various strategies that USBP can apply. One strategy might differ from another in the way the candidate defensive actions are chosen, or number of available assets that can be used, etc. (Note that USBP can apply two different types of defensive actions, and we can evaluate the contribution of both individually or in concert with each other.)

## A. SCENARIO A: A SURPRISE VEHICLE INFILTRATION

If USBP commits no assets to secure the border, the infiltrator will choose the minimum-risk path based on the intrinsic risk of each arc (e.g., the probability that a local resident will call USBP to report people trespassing). We define this as a *surprise infiltration*. The minimum-risk infiltration is shown Figure 12.

## B. SCENARIO B: OPTIMAL USBP ASSET ALLOCATION AGAINST A SURPRISE VEHICLE INFILTRATION

Assuming the infiltrator can't observe USBP's pre-positioning of its assets, but that USBP actually has perfect intelligence of where the surprise intrusion will occur, we can optimize USBP's asset allocation accordingly. Figure 13 illustrates the optimal defensive plan to interdict such an intrusion. The infiltrator still achieves a probability of escape of 0.4, even when he chooses a path in the mistaken belief USBP has no interdiction assets.

## C. SCENARIOS C AND D: A VEHICLE INFILTRATION AND INTERDICTION PLAN ASSUMING TRANSPARENCY OF USBP'S ASSETS

If the infiltrator knows USBP preparations in advance, he will seek to minimize his probability of capture by selecting an optimal evasive infiltration plan. The infiltrator anticipates a certain probability of getting caught --- the risk of the path he chooses. From USBP's perspective, the problem is to decide which defensive actions to employ such that the maximum probability of escape the infiltrator can achieve is minimized. The USBP also anticipates a certain probability of the infiltrator getting through. If the infiltrator chooses a path other than the anticipated optimal path, then the USBP is better off. If the USBP prepositions its assets in a way different from the anticipated optimal interdiction plan, the infiltrator has even more chance of escape.

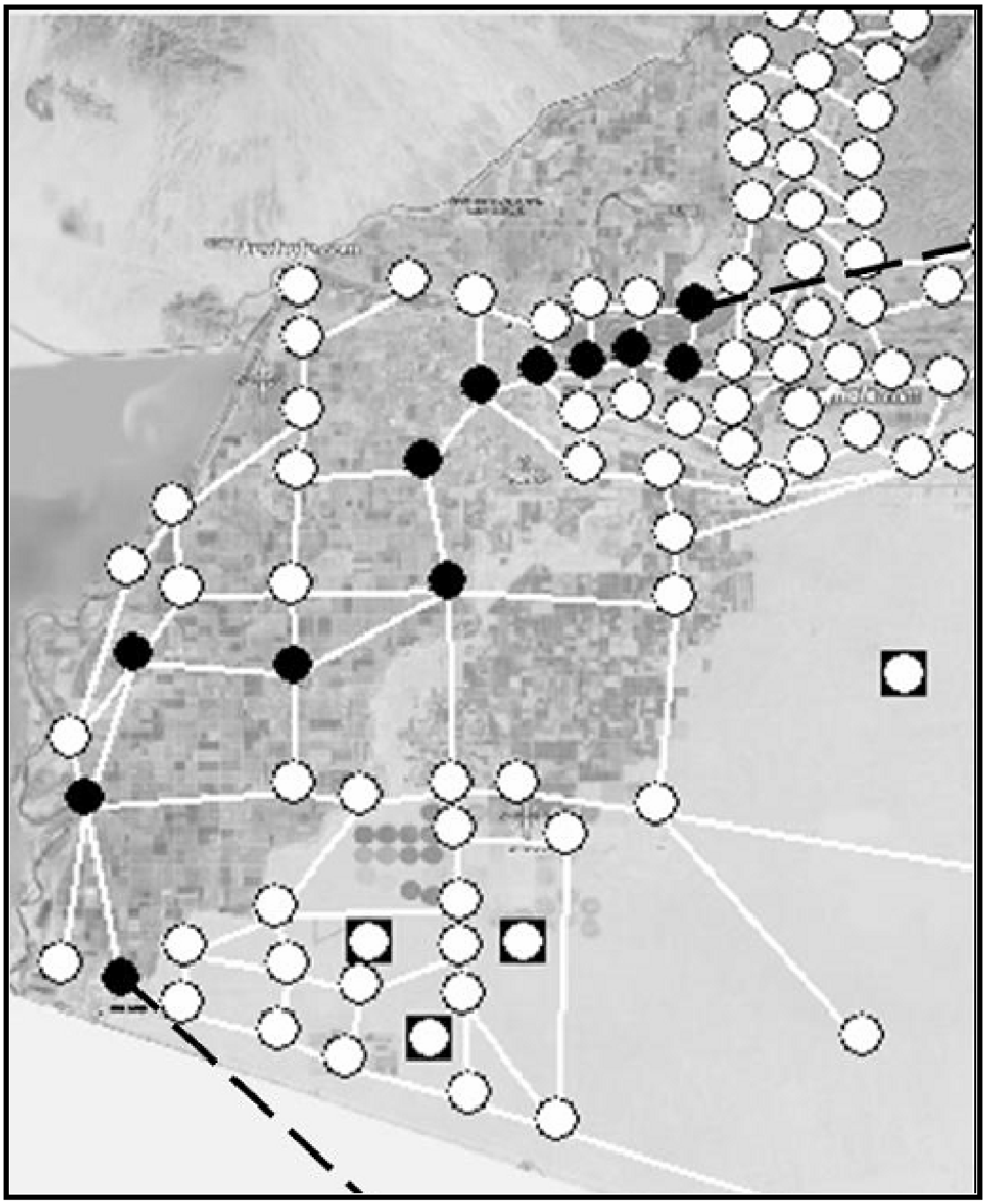

Figure 12. Scenario A: A Surprise Vehicle Infiltration through Downtown Yuma
White ovals are road intersections, and black rectangles with white ovals on them are centers of land parcels. Black ovals are the nodes on the infiltrator's path. Dashed lines represent artificial arcs that are entry and exit ways into AOR. The USBP employs no assets to interdict this infiltration. The probability of capture is based on the exposure time of the infiltrator in AOR. This is a surprise intrusion that minimizes the infiltrator's risk if he knows that USBP has no defenses.

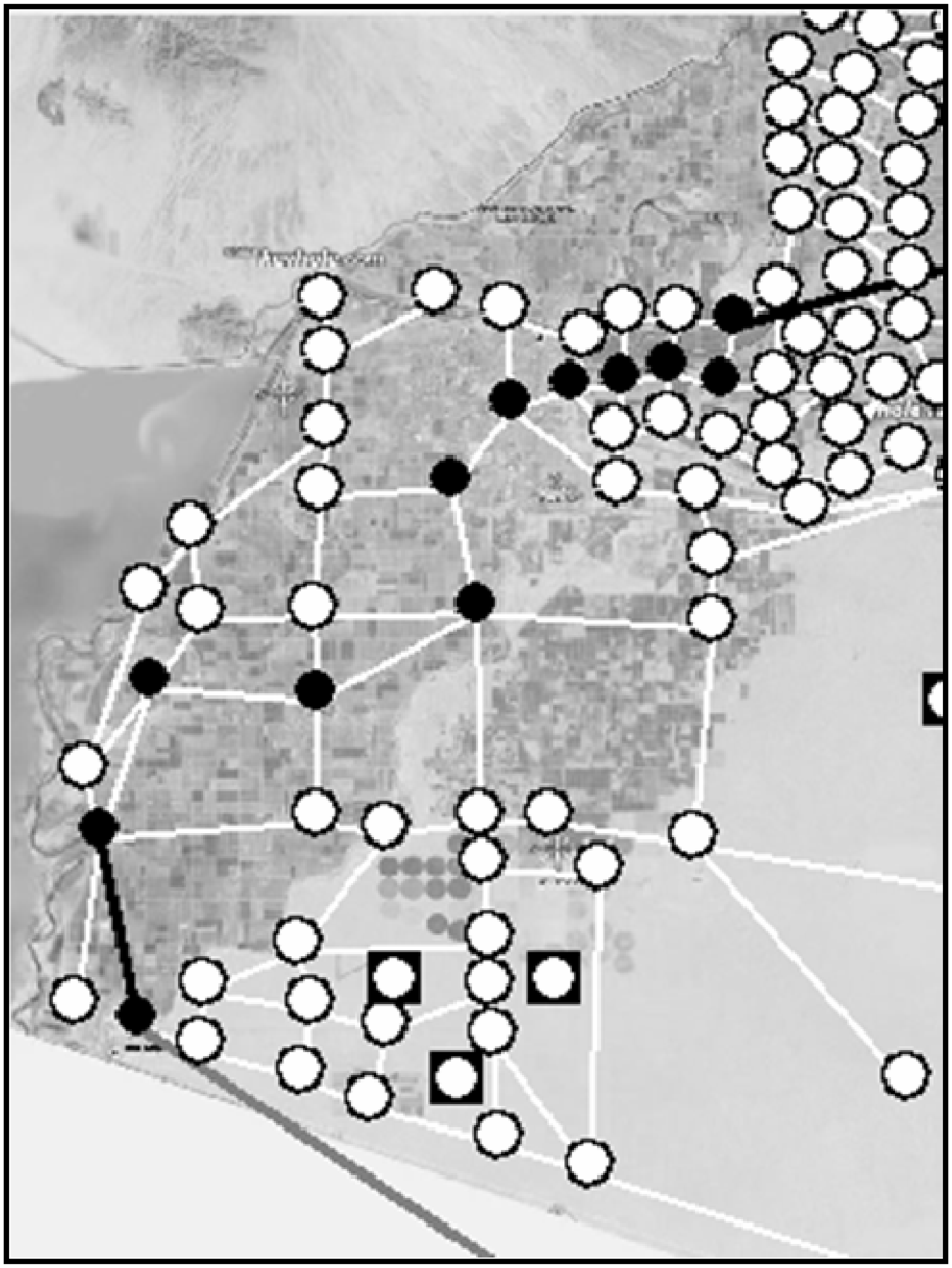

Figure 13. Scenario B: A Surprise Interdiction of a Vehicle Infiltration
White ovals are road intersections, black rectangles with white ovals on them are centers of land parcels, and the black ovals are the nodes on the infiltrator's path. The gray arc is defended by a sensor. The black arcs are defended by checkpoints. Note that the sensor is backed up by a check point. If detection is made by that sensor, personnel from the near-by check point capture the infiltrator. In our model, the USBP has very limited assets to use in urban areas (e.g., we assume that road patrol and heli-patrol are not efficient in an urban area). The infiltrator gets a high return in the urban area because of these limitations (i.e., the probability of escape is as high as 0.4 even under the mistaken belief that USBP has no interdiction assets).

In Scenario C, the USBP can employ one check point, one remote observation post, two road patrols, sensors to cover at most 15 road segments, and one helicopter. The solution from this two-sided model is shown in Figures 14 and 15. The infiltrator escapes with a probability of 0.93. This intrusion takes place in downtown Yuma. Downtown Yuma offers a cheap intrusion in terms of probability of capture, because the USBP has limited assets there. The only effective means of detection and capture in downtown Yuma is the use of check points. With one *visible* check point, the interdictor can circumnavigate, and USBP can't make the necessary cut to divert the intrusion from downtown Yuma to the desert.

In Scenario D, the USBP can employ two check points, two remote observation posts, two road patrols, sensors to cover at most 15 road segments, and one helicopter. A solution is shown in Figures 15 and 16. The infiltrator escapes with a probability of 0.89. The probability of escape is high in these cases because of the assumption of transparency of USBP's assets. Each time the infiltrator sees a check-point he can go around it and avoid capture, unless USBP has enough check points to stop all such evasions.

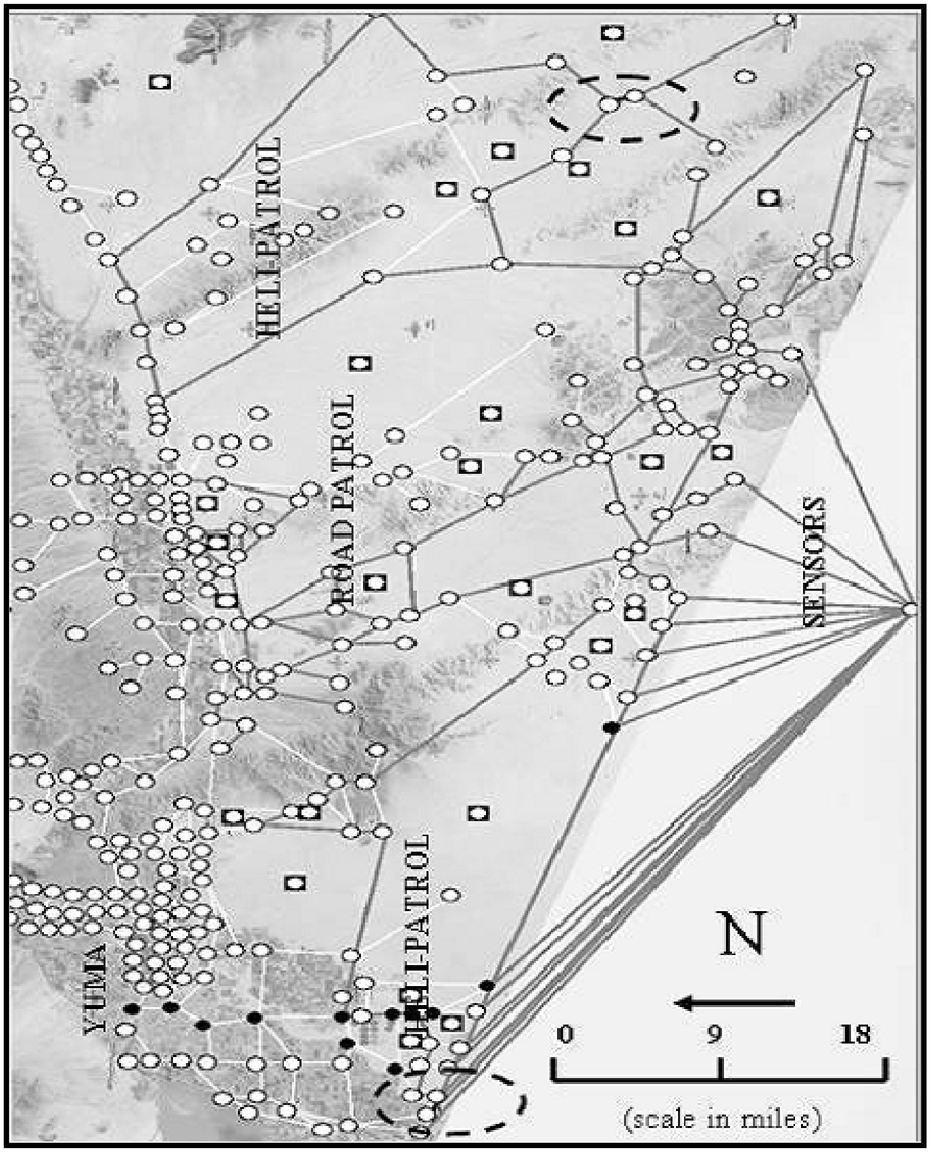


Figure 14. Scenario C: A Vehicle Infiltration through Downtown Yuma (Transparency of USBP's assets)

White ovals are road intersections, black rectangles are centers of land parcels, and the black ovals are the nodes on the infiltrator's optimal path. The gray arcs are defended by detection actions, and the black arcs are defended by capture actions. Check points and remote observation posts are marked by a dashed-line ellipse. Details of where different actions interact are not shown for clarity. Each detection action is supported with a capture action. The USBP allocates one check point, one remote observation post, two road patrols, sensors to cover at most 15 road segments, and one helicopter. (Our solution provides capture actions close enough to detection options to increase the probability of capture.) The probability of capture is 0.08. This is the best the USBP can do if the infiltrator can anticipate all defensive actions. Focus on the allocation of assets rather than the probability of capture.

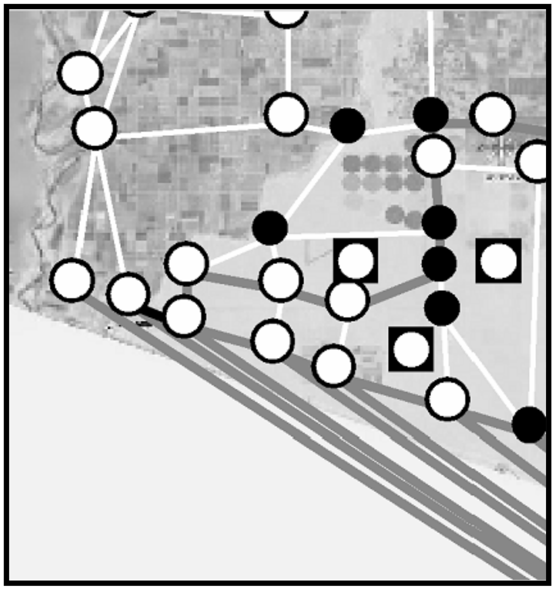

Figure 15. Relationship between a Capture Action and a Detection Action in Our Solution

This is a blown-up view of the checkpoint in downtown Yuma. The white ovals are the road intersections, black rectangles with white ovals on them are centers of land parcels, and the black ovals are the nodes on the infiltrator's path. The gray arcs are defended by detection options. The black arc is defended by a check point. If detection occurs on any of these gray arcs, the capture action (a check point in this case) carries out the search to lead to capture of the infiltrator.

### D. SCENARIO E: OPTIMAL INTERDICTION PLAN AGAINST INFILTRATION ON FOOT

We solve a sample problem where the USBP can employ one check point, one remote observation post, two road patrols, sensors to cover at most 15 road segments, one helicopter and one off-road operation. We adjust infiltrator transition times and arcs to represent travel on foot. A solution is shown in Figure 18.

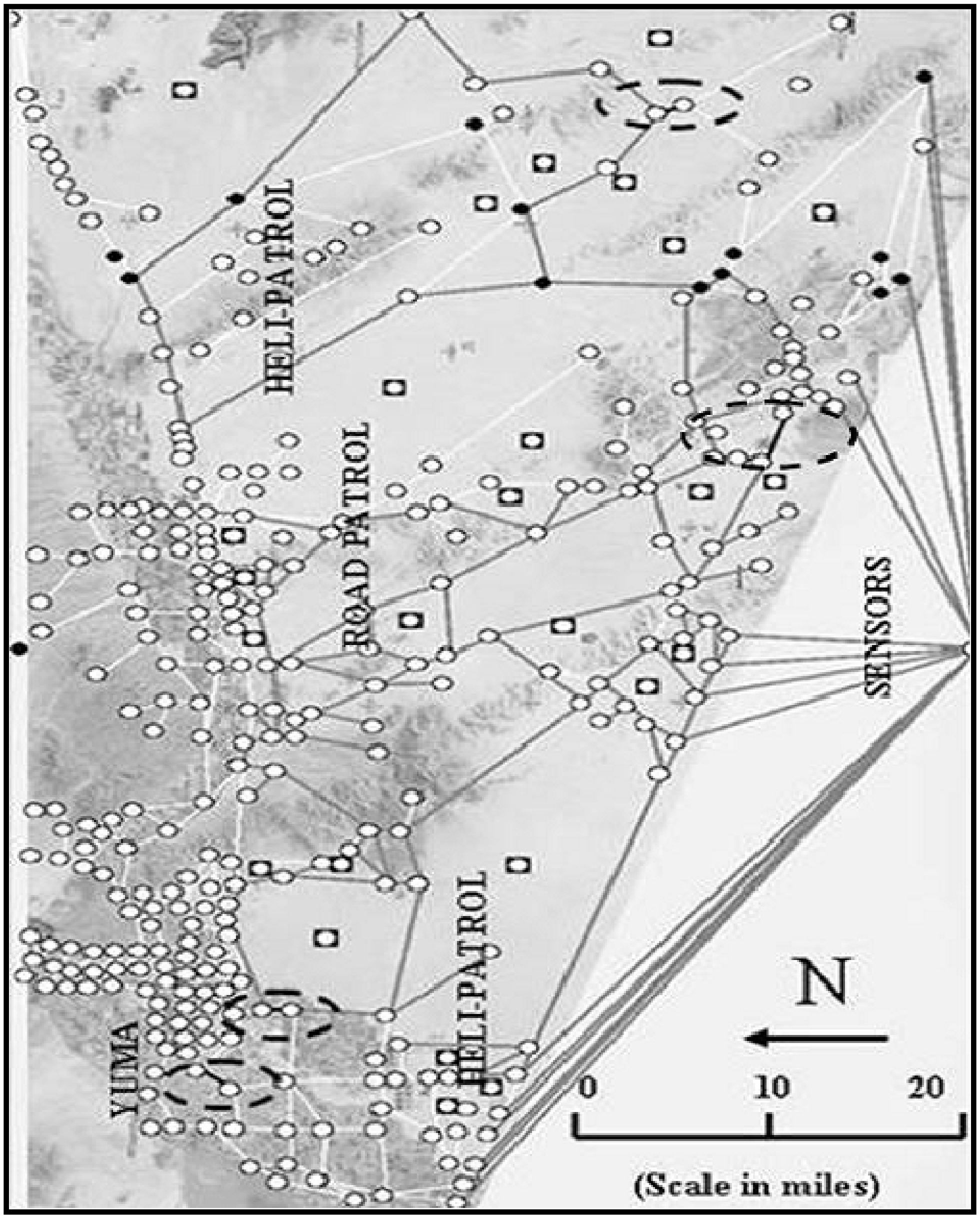


Figure 16. Scenario D: Transparency of USBP's assets (diverting the vehicle infiltration from downtown Yuma to the desert)

White ovals are road intersections, black rectangles are centers of land parcels, and the black ovals are the nodes on the infiltrator's optimum path. The gray arcs are defended by detection actions, and the black arcs are defended by capture actions. Check points and remote observation posts are marked by a dashed-line ellipse. Details of where different actions interact are not shown for clarity. The USBP allocates two check points, two observation posts, two road patrols, sensors to cover at most 15 road segments, and one helicopter. The probability of capture increases to 0.11 from 0.08. More importantly, the infiltration is diverted from downtown Yuma to the desert.

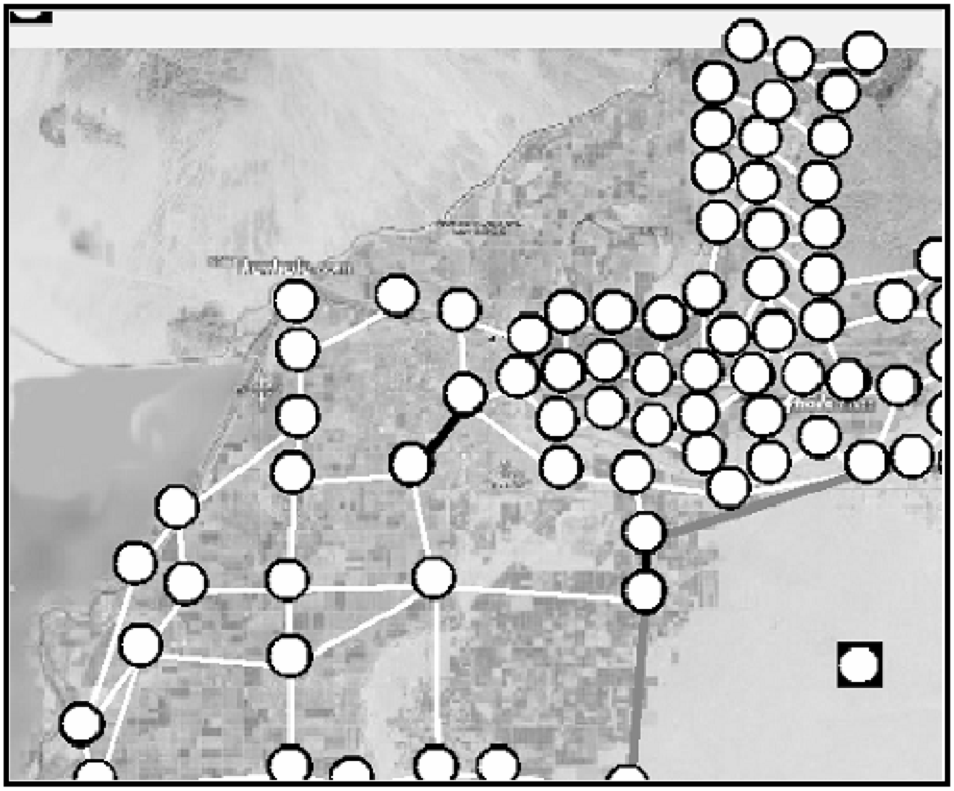

Figure 17. Check-Points Identifying The Critical Arcs which, Once Defended, Will Make the Intrusion through Downtown Yuma More Expensive than the Desert
The white ovals are the road intersections, black rectangles with white ovals on them are centers of land parcels. The black arcs are defended by check points.

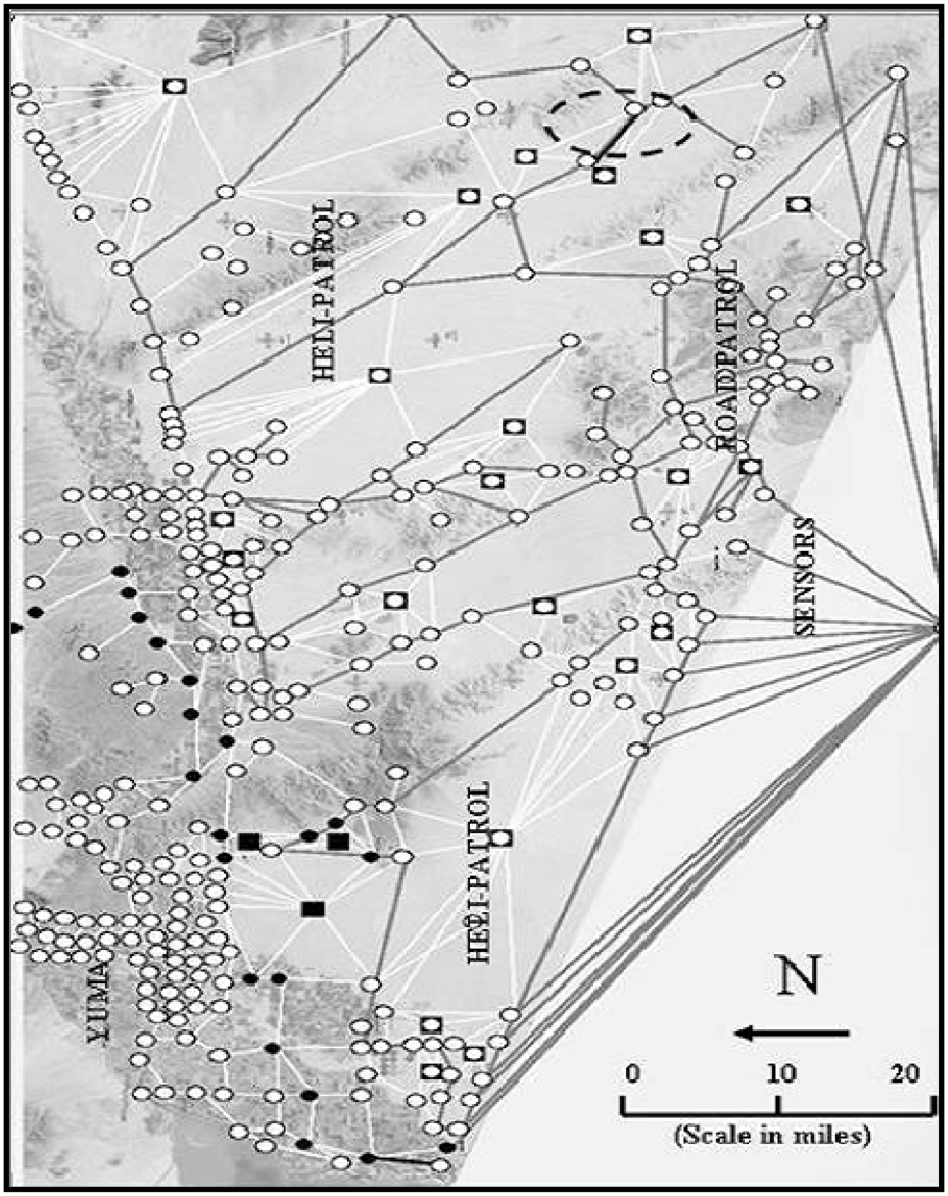


Figure 18. Scenario E: An Optimal Plan to Interdict an Intruder on Foot (Transparency of USBP's assets)

White ovals are the road intersections, black rectangles with white ovals on them are centers of land parcels, and the black ovals and black rectangles are the nodes on the infiltrator's optimal path. Black rectangles are centers of land parcels that the infiltrator traverses. The infiltrator on foot accepts a certain initial risk at the time of entry into the U.S., and thereafter plans to exploit terrain, and avoid detection or capture. The probability of capture is 0.11.

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# IV. CONCLUSION

We have introduced a mixed integer linear program that expresses a border security problem mathematically. We study two different cases, one a vehicle intruder, and one an intruder on foot, where the infiltrator can see the USBP's preparations and where he can't. We evaluate different strategies and USBP's use of different resources to interdict an unauthorized entry into the U.S. Our implementation best addresses a well-planned, signal infiltration --e.g., a one-time smuggling of a weapon of mass destruction.

We use probability of capture as the measure of effectiveness. We make a distinction between actions that can only lead to detection and actions that can also lead to capture in addition to detection. This distinguishing feature reflects the interaction between different types of defensive actions. Our model provides insight for border security planners by identifying critical road segments, areas and land parcels to be defended to preclude evasion of visible interdiction actions, and effects of employing different types of assets and strategies on the infiltration patterns.

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